The Current Understanding on the UV Upturn
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The Current Understanding on the UV Upturn

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Abstract. The unexpected high bump in the UV part of the spectrum found in nearby giant elliptical galaxies, a.k.a. the UV upturn, has been a subject of debate. A remarkable progress has been made lately from the observational side, mainly involving space telescopes. The GALEX UV telescope has been obtaining thousands of giant ellipticals in the nearby universe, while HST is resolving local galaxies into stars and star clusters. An important clue has also been found regarding the origin of hot HB stars, and perhaps of sdB stars. That is, extreme amounts of helium are suspected to be the origin of the extended HB and even to the UV upturn phenomenon. A flurry of studies are pursuing the physics behind it. All this makes me optimistic that the origin of the UV upturn will be revealed in the next few years. I review some of the most notable progress and remaining issues.

1. Introduction

A review on the UV upturn phenomenon may usually start with a following or similar definition: "a bump in the UV spectrum between the Lyman limit and 2500Å is found *virtually in all bright spheroidal galaxies*" (e.g., Yi & Yoon 2004). This seems no longer true! While earlier studies based on a small sample of nearby galaxies led us to think so, a much greater sample from the recent GALEX database appears to disprove it. Only a small fraction of elliptical galaxies show a strong UV upturn and it is generally limited to the brightest cluster galaxies (Yi et al. 2005). This review is about the recent development on this seemingly-old topic. I recycle some of the contents in my earlier review given in the first Hot Subdwarf and Related Objects workshop held in Keele, UK (Yi & Yoon 2004). For a more traditional review, readers are referred to the articles of Greggio & Renzini (1999) and O'Connell (1999).

2. Previous observations

The UV upturn has been a mystery ever since it was first found by the OAO-2 space telescope (Code & Welch 1979). According to the opacity effect more metal-rich populations show redder colours, and hence giant elliptical galaxies were not expected to contain any substantial number of hot stars to show a UV upturn. Yet, it was confirmed by subsequent space missions, ANS (de Boer 1982), IUE (Bertola et al. 1982) and HUT (Brown et al. 1997). Figure 1 shows an example spectrum of the giant elliptical galaxy NGC 4552 mosaicked from multi-band measurements.

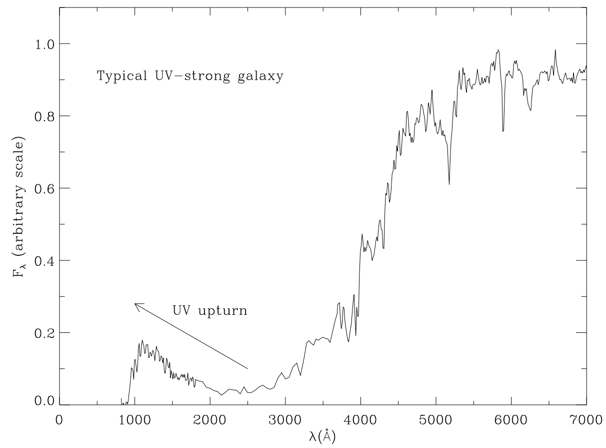

Figure 1. The composite spectrum of the giant elliptical galaxy NGC 4552 shows a classic example of the UV upturn. The mosaic spectrum is originated from HUT (FUV), IUE (NUV), and ground-based telescope (optical). Excerpted from Yi, Demarque, & Oemler (1998).

Some of the observational findings based on the nearby bright elliptical galaxies are particularly noteworthy. The positive correlation between the UV-to-optical colour (i.e., the strength of the UV upturn) and the Mg2 line strength found by Burstein et al. (1987) through IUE observations has urged theorists to construct novel scenarios in which old ($\gtrsim$ a few Gyr) metal-rich ($\gtrsim Z_\odot$) populations become UV bright (Greggio & Renzini 1990; Horch et al. 1992; Dorman et al. 1995). Also interesting was to find using HUT that, regardless of the UV strength, the UV spectral slopes at 1000–2000Å in the six UV bright galaxies were similar suggesting a very small range of temperatures of the UV sources in these galaxies (Brown et al. 1997), which corresponds to $T_{\rm eff} \approx 20,000 \pm 3,000\,$K. In fact, the characteristic temperature of the UV sources seems strangely somewhat *lower* in a *stronger* UV-upturn galaxy (Yi et al. 1998).

3. Theory

Theorists aim to present a model that explains three basic observational facts:

1. UV upturn being present in bright elliptical galaxies
2. the positive correlation between the strength of the UV upturn and the *optical* metal line (Mg2) strength, and
3. a narrow range of temperature of UV sources.

Young stars are difficult to satisfy these facts and thus thought unlikely to be the main driver of the UV upturn. The focus has been on how an old population can develop hot stars. Post-AGB stars (central stars of planetary nebulae) are

too short-lived and more fatally too hot most of their lifetime, hence violating *item* 3. There is a good consensus that hot (low-mass) horizontal-branch (HB) stars are the more natural candidates. Here I introduce two classical solutions based on the HB hypothesis.

3.1. Metal-poor HB hypothesis

It is widely known that metal-poor HB stars can be hot and make good UV sources when they are old (e.g., Lee et al. 1994). Thus, the first scenario was naturally that an order of 20% of the stellar mass of bright elliptical galaxies are extremely old and metal-poor populations (Park & Lee 1997). The strength of this scenario is that the oldest stars in a galaxy are likely the most metal-poor and to be in the core, where the UV upturn is found to be strong. In this scenario, the UV vs Mg2 relation does not present any causality connection but simply a result of tracing different populations in terms of metallicity. Mg2 is exhibited by the majority metal-rich stars while the UV flux is dominated by the old metal-poor stars. The narrow range of temperature is easily explained as well. On the other hand, the mass fraction of order $\sim$ 20% is too high by the standard galactic chemical evolution theory. Canonical models suggest the metal-poor fraction of $\lesssim$ 10%. If metal-poor stars are present at such a high level, there must also be a large number of intermediate-metallicity (20–50% solar) stars, which will make galaxy's integrated metallicity too low and integrated colours too blue, compared to the observed values. Moreover, the age of the oldest stars, i.e. the main UV sources, is required in this scenario to be 20–30% older than the average Milky Way globular clusters (Yi et al. 1999). This would pose a big challenge but there may be a rescue (see §4).

3.2. Metal-rich HB hypothesis

Through a gedanken experiment Greggio & Renzini (1990) noted a possibility that extremely low-mass HB stars may completely skip the AGB phase and dubbed it "AGB Manqúe stage". Through this stage metal-rich populations could become UV bright. This is particularly effective for a high value of helium abundance (Dorman et al. 1995). If galactic helium is enriched with respect to heavy elements at a rate of $\Delta Y/\Delta Z \gtrsim 2.5$ this means that the stage would be very effective in galaxy scales as well (Horch et al. 1992). It could be similarly effective if the mass loss rate in metal-rich stars is 30–40% higher than that of metal-poor stars (Yi et al. 1997a). Either of the two conditions would be sufficient while they can also complement each other. Both of these conditions are difficult to validate empirically but plausible (Yi et al. 1998). In this scenario, metal-rich stars may become UV bright in two steps: (1) they lose more mass on the red giant phase due to the opacity effect and become low-mass HB stars, and (2) extremely low-mass HB stars stay in the hot phase for a long time and directly become white dwarfs, effectively skipping the red, asymptotic giant phase (Yi et al. 1997a, 1997b). This scenario reproduces most of the features of the UV upturn (Bressan et al. 1994; Yi et al. 1998). The UV vs Mg2 relation is naturally explained as a UV vs metallicity relation. However, its validity heavily hinges upon the purely-theoretical (and hence vulnerable to criticisms) late-stage stellar evolution models of metal-rich stars.

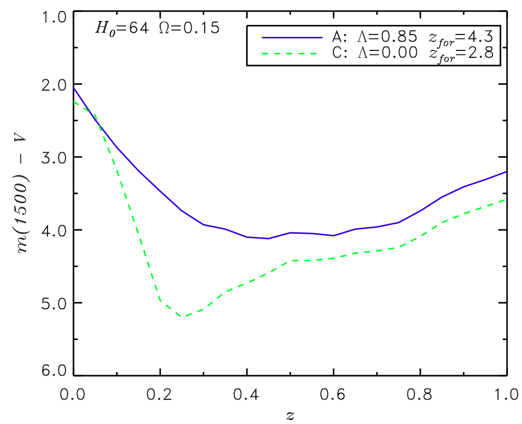

Figure 2. The two classic models (Model A: metal-poor HB, Model C: metal-rich HB) predict different evolution history. While precise calibrations are difficult, the UV developing pace is in general predicted to be faster for more metal-rich populations. Excerpted from Yi et al. (1999).

3.3. Metal-poor or metal-rich HB?

Both of these scenarios are equally appealing but their implications on the age of bright elliptical galaxies are substantially different. The metal-poor hypothesis suggest UV-upturn galaxies are 30% older than Milky Way and requires the universe to be older than currently believed, suggesting a large cosmological constant. The metal-rich hypothesis on the other hand suggests that elliptical galaxies are not necessarily older than the Milky Way halo.

4. Issues

Readers may get an impression by reading the previous sections that we have solid and successful theories. Quite contrarily, there are several critical issues to be understood before we can ever claim so.

4.1. α-enhancement

Theorists (including myself) often interpret the UV vs Mg2 relation as a metallicity effect on the UV flux. However, it should be noted that Mg2 strength may not be representative of the overall metallicity. In fact, it has been known that elliptical galaxies are enhanced in α-elements with respect to iron. We then naturally wonder if it is not the overall metallicity but α-enhancement that generates the UV upturn. To perform this test, we need α-enhanced stellar models. The Y^2 Isochrones group have released their α-enhanced stellar models for the main sequence (MS) through red giant branch (RGB) (Kim et al. 2002). But, no α-enhanced HB models are publicly available yet. α-enhancement can have several impacts on the galaxy spectral evolution. First, it changes the stellar evolutionary time scale, as CNO abundance affects the nuclear generation rates.

Second, it changes opacities and thus the surface temperatures of stars. These two effects will make a change in the mass loss computed using a parameterised formula, such as the Reimers (1975) formula. For a fixed mass loss efficiency, we find the α-enhanced ([α/Fe]=0.3–0.6) tracks yield $\approx 0.03 M_{\odot}$ smaller mass loss at ages 5–8Gyr but $\approx 0.03 M_{\odot}$ greater mass loss at ages $\gtrsim 8\,$Gyr, compared to the standard ([α/Fe]=0) tracks. α-enhancement must have similar opacity effects on the HB evolution, while its effect on the mass loss on the HB should be negligible. Thus its effects are expected to be greater to the MS to RGB than to the HB phase. Considering this, I have decided to inspect the overall effects of α-enhancement by just adopting new α-enhanced MS through RGB tracks, ignoring the change in the HB models. My earlier review (Yi & Yoon 2004) shows the results for two metallicities and three values of α-enhancement. It can be summarised as follows. In old metal-poor models α-enhancement causes a positive effect to the *relative* UV strength because (1) it causes a slight increase in mass loss on the RGB and (2) it causes MS stars and red giants to be redder and fainter in V band. The [α/Fe]=0.3 model roughly reproduces the SED of a typical UV-strong metal-poor globular cluster, which is satisfying. The metal-rich models on the other hand do not show any appreciable change in response to α-enhancement. Because giant elliptical galaxies are largely metal-rich (roughly solar) and the light contribution from metal-poor stars is not substantial, it is unlikely for α-enhancement to play a major role to the UV upturn.

4.2. EHB stars in star clusters

With the HST spatial resolution, a number of studies have found hot, extended horizontal branch (EHB) stars in globular clusters (e.g., Piotto et al. 1999). They are efficient UV sources and important candidates for the main UV sources in elliptical galaxies; but canonical population synthesis models have difficulty reproducing them as they are observed (number density, colours and brightness).

NGC 6791 is a particularly interesting case. This old (8-9Gyr) metal-rich (twice solar) open cluster is unique resembling the stellar populations of the giant elliptical galaxies. Strikingly, 9 out of its 32 seemingly-HB stars have the properties of typical EHB stars (Kaluzny & Udalski 1992; Liebert et al. 1994), while canonical models do not predict any (Yong et al. 2000). It is critical to understand the origin of these *old hot metal-rich stars*. Landsman et al. (1998), based on UIT data, concluded that NGC 6791, if observed from afar without fore/background stellar contamination, would exhibit a UV upturn just like the ones seen in elliptical galaxies.

Through detailed synthetic HB modelling we found that it is impossible to generate an HB with such a severely-bimodal colour distribution as shown in this cluster, unless an extremely (and unrealistically) large mass dispersion is adopted. In the hope of finding a mechanism that produces such an HB Yong et al. (2000) explored the effect of mass loss *on* the HB. Yong et al. found that with some mass loss taking place on the HB ($\approx 10^{-9} - 10^{-10}\, M_{\odot}\, yr^{-1}$) HB stars born cool quickly become hot, suggesting that mass loss on the HB might be an effective mechanism of producing such stars. Vink & Cassisi (2002) however pointed out that the level of the mass loss assumed by Yong et al. is too high to justify in their radiation pressure calculations in the context of single-star evolution. Green et al. (2000) reported that most of these hot stars in

NGC 6791 are in binary systems. If they are close binaries and experience mass transfer it would be an effective mechanism for mass loss. But at the moment it is difficult to conclude whether binarity had causality on their EHB nature or not.

4.3. Binaries

SdB/O stars, the central objects of this conference, may be the field counterparts of the EHB stars in clusters. They have the properties similar to those of the UV sources in the UV-upturn galaxies. Surprisingly, more than 70% of sdB stars are found to be in binary systems (Saffer et al. 2000; Maxted et al. 2001).

Han et al. (2003) used a binary population synthesis technique to study the effects of binary evolution and found that 75–90% of sdB stars should be in binaries. SdBs are detected to be in a small mass range centred at $0.5\,M_{\odot}$, but Han et al. found that the range should be in truth as wide as 0.3 through 0.8 $M_{\odot}$. They predict a birthrate of 0.05 yr^{-1} for Population I stars and 6 million sdB stars in the disc. Assuming the Galactic Disc mass of $5\text{x}10^{10}\,M_{\odot}$, this means roughly 100 sdB stars per $10^6 M_{\odot}$. In a back-of-the-envelope calculation, there are roughly a few thousand HB stars per million solar mass in globular cluster populations. A comparison between the sdB rate (100 per $10^6 M_{\odot}$) and that of the HB (say, 5000 per $10^6 M_{\odot}$) suggests that an old disc population may develop 1 sdB star for 50 HB stars (2%). This sounds by and large reasonable from the EHB-to-HB number ratio found in globular clusters. But it is hardly impressive from the perspective of searching for copious UV sources in galaxies. For comparison, NGC 6791 has roughly 30% (8 EHB-like stars out of 32 HB-like stars) and the UV-brightest Galactic globular cluster ω Cen has 20%. These two examples show an order of magnitude higher values of EHB-to-HB ratio than deduced from a simple estimation based on the binary population synthesis models. Yet, even ω Cen does not exhibit a UV upturn as observed in giant elliptical galaxies: $FUV\!-\!V$ is comparable but $FUV\!-\!NUV$ is 1–2 magnitudes redder than found in ellipticals. If this calculation is realistic at least within an order, binary mass transfer may not be sufficient to provide the origin of the majority of the UV sources in UV-upturn galaxies. On the other hand, a larger sdB production rate might be plausible in elliptical galaxy environment due to large age and/or large metallicity.

A considerably more detailed investigation was presented by Han et al. (2007). They constructed the population synthesis models including binaries of varied properties (in mass ratio and separation). The conclusions from their prediction can be summarised as (1) most of the UV light of ellipticals comes from binary sdB stars (2) a UV upturn starts to appear as early as when the galaxy is 1.5Gyr old (3) and the $FUV\!-\!V$ colour stays virtually constant since then. This is an important prediction because this is the first study that realistically consider binary products in population models. One immediately notices that the item (3) contradicts the single-star population models of Yi et al. (1999) discussed in §3.3 and Figure 2.

4.4. Other issues

There are other important issues as well. For example, the late-stage flash mixing scenarios and the like (D'Cruz et al. 1996; Brown et al. 2001) may also

be effective ways of producing hot stars (such as sdB stars) in old populations. Their typical temperature range ($T_{\rm eff} \gg 20,000\,{\rm K}$) and the predicted birthrate may not be entirely consistent with the UV upturn shown in elliptical galaxies, however.

Another important observational constraint comes from the HST UV images of M32. First, Brown et al. (2000) found that PAGB stars are two orders of magnitudes fewer than predicted by simple stellar evolution theory. This is significant as PAGB stars are thought to account for 10–30% of the UV flux in the UV-upturn galaxies (Ferguson & Davidsen 1993). More importantly, they find too many *faint* hot HB stars to reproduce with standard population models that are based on the mass loss rate calibrated to the globular cluster HB morphology. It is possible to reproduce the observed number of hot stars in M32-type populations if a greater mass loss rate is used, which would be consistent with the variable mass loss hypothesis (Willson et al. 1996; Yi et al. 1997b, 1998). But theoretical justification is a problem again.

5. GALEX observations

The single star population synthesis models (§3.3) predict a rapid decline in $FUV-V$ with increasing redshift (lookback time), while the binary models suggest no significant change. This stark contrast provides an important test.

GALEX is NASA's UV space telescope mission that can do just this. It has sensitive FUV and NUV detectors and reaches passive (no star formation) old populations (such as many elliptical galaxies) out to $z \sim 0.2$ (Martin et al. 2005). Its Deep Imaging Survey (DIS) is obtaining the UV images of tens of galaxy clusters using $\gtrsim 20,000$ seconds of exposure. The UV upturn is found to be the strongest in the brightest cluster elliptical galaxies (BCGs) and hence we have tried to obtain accurate photometric data on the BCGs in our galaxy cluster sample. Besides, a number of lower-redshift ($z \sim 0.1$) BCGs have been sampled from the shallower Medium-deep Imaging Survey (MIS) as described in Schawinski et al. (2007). The UV photometry turned out to be very tricky because there are many background UV sources that are not easily identifiable in shallow images. The background confusion would easily cause underestimation on the UV brightness. Occasionally, small foreground objects that are invisible in the optical images contaminate the UV flux of our target galaxy as well.

From the up-to-date GALEX database, Ree et al. (2007) obtained the data for seven BCGs from DIS and five from MIS. A small fraction of the BCGs had star formation signatures (Yi et al. 2005) and hence had to be removed from our sample. Figure 3 shows the look-back time evolution of the apparent (not $K-$corrected) $FUV - V$ colour for the BCGs at $z < 0.2$. The FUV flux fades rapidly with redshift. The colours are derived from total magnitudes to minimize aperture effect. Model lines are calibrated to the colour range ($FUV - V = 5.4 - 6.4$) of the giant elliptical galaxies in nearby clusters (*open circles*), and passively evolved and redshifted with look-back time so that they can be directly compared with the observed data of the BCGs (*filled circles*) in GALEX DIS (black) and MIS (grey) mode. The size of circle symbols represents the absolute total luminosity in r-band. The solid and dashed lines are from the passively evolving UV-to-optical spectra of the "metal-

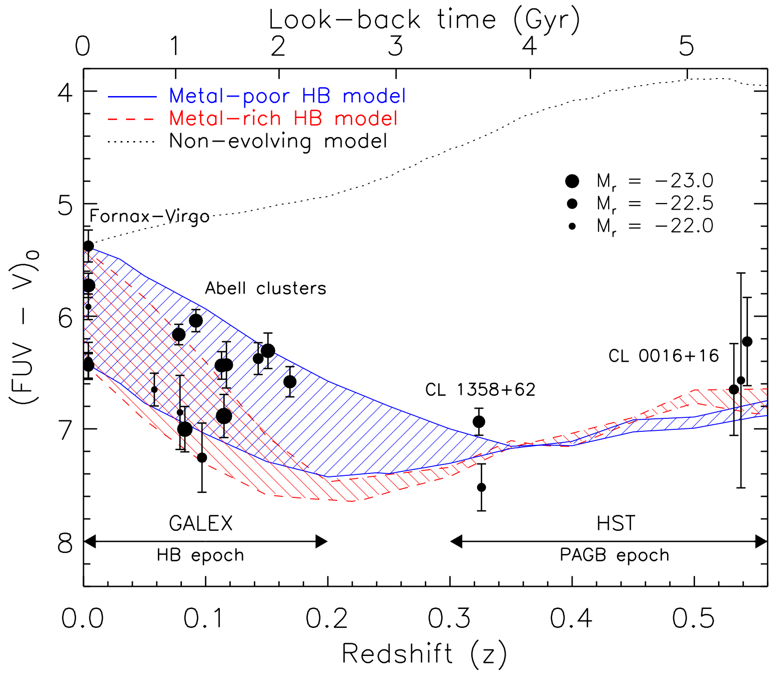

Figure 3. Look-back time evolution of the apparent (not $K-$corrected) $FUV-V$ colour for the brightest cluster elliptical galaxies (BCGs) at $z \lesssim 0.2$. FUV flux fades rapidly with redshift which is consistent with the prediction from the single-star population models (§3.3). See text for details. Excerpted from Ree et al. (2007).

poor" and "metal-rich" HB models (§3). The regions filled with oblique lines denote the predicted colour range from these two extreme models. The dotted line indicates the apparent colour expected when the local UV upturn galaxy NGC 1399 model spectrum is redshifted without the effect of stellar evolution. The binary population models would be similar to the non-evolving model. The higher redshift data points at 0.33 and 0.6 are the HST data from Brown et al. (2000, 2003) The model fits by Ree et al. (2007) and Lee et al. (2005a) suggest that *the GALEX data show a UV flux decline with lookback time at the rate* $\Delta(FUV-V)/\Delta t = 0.54$ *mag/Gyr.* Although a definite answer requires more data, the current sample seems more consistent with the prediction from the single-star population models. Any population model aiming to explain the UV upturn phenomenon would be obliged to reproduce this unique data.

6. New issue: enhanced-helium population

A remarkable new information has recently emerged. Observations for the colour-magnitude diagrams on globular clusters ω Cen and NGC 2808 revealed the multiple nature of their stellar populations. The most massive globular cluster ω Cen for example is now known to have up to four different metallicities

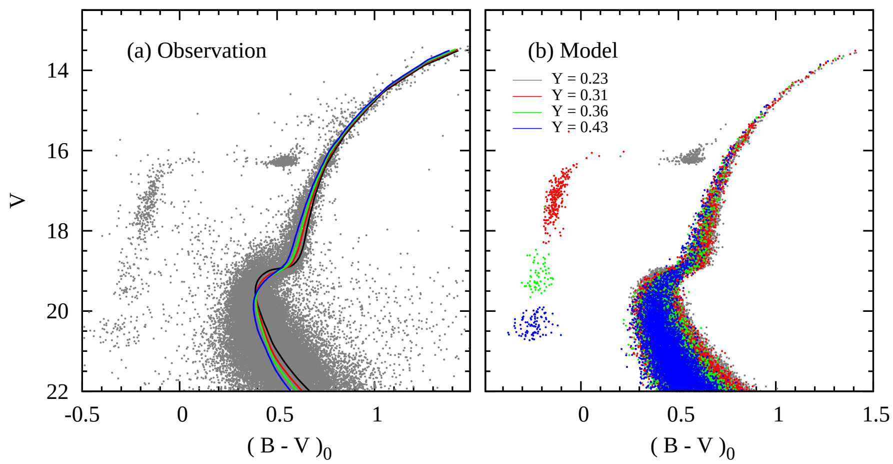

Figure 4. The observed and modeled colour-magnitude diagrams of the globular cluster NGC 2808. *left*: The cluster shows an exceptionally wide distribution of horizontal branch stars. *right*: It can be precisely reproduced by theory for example by assuming a large range of helium abundance. Excerpted from Lee et al. (2005b)

both for the main sequence and the red giant branch (Anderson 2002; Bedin et al. 2004). Most shockingly, the bluest main sequence is found spectroscopically to be more metal-rich (Ferraro et al. 2004) which implies an extremely high helium abundance of $Y \approx 0.4$. Interestingly, Lee et al. (2005b) noted that such a helium-rich stellar population would evolve into extremely hot HB explaining the hitherto mysterious origin for the EHB stars of ω Cen. Lee et al. claims that the same phenomenon is seen in NGC 2808 as well. Such a high helium abundance could in fact be more mysterious than the origin of the EHB stars itself, hence became a hot topic. The high value of helium abundance ($Y \approx 0.4$) seems particularly impossible when it is combined with its low metallicity empirically constrained ($Z \approx 0.002$–0.003). This leads to $\Delta Y/\Delta Z \approx 70$ which is extremely unlikely from the galactic chemical enrichment point of view unless some exotic situation is at work, such as the chemical inhomogeneity in the proto-galactic cloud enriched by first stars (Choi & Yi 2007).

No matter what the physical process may be, the CMD fits unanimously suggest that the high value of helium is the easiest solution. Figure 4 shows Lee et al. (2005b)'s comparison between the observed and model CMDs assuming that the hot end of the HB morphology is primarily governed by the variation in the helium abundance. The reproduction is impressive. If the EHB is indeed produced by helium variation, then, it almost seems that we are going back to two decades ago in terms of the debate on the second parameter for the HB morphology (see Lee et al. 1994). According to Lee et al. (2007), a pronounced EHB is more easily found among more massive globular clusters, which forces us to think deeply about the nature of globular clusters in general.

It is not yet clear whether the enhanced helium interpretation is physically plausible and whether it can be similarly significant to the galaxy scale where

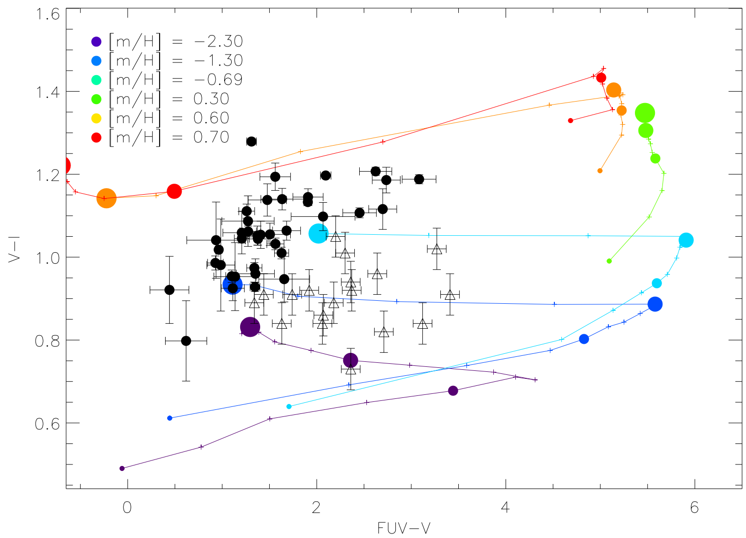

Figure 5. Model (FUV V) versus (VI) grid for a range of metallicities and ages, generated from stellar models with the fiducial value of He enrichment (Y/Z = 2). The lowest age plotted is 1 Gyr and the largest age plotted is 15 Gyr. Ages 1, 5, 10 and 15 Gyr are shown using filled circles of increasing sizes. The globular cluster data of M87 (filled circles) and Milky Way (open triangles) with errors are overplotted. It is apparent that the M87 photometry lies outside the age range 1-14 Gyr for all metallicities. Excerpted from Kaviraj et al. (2007).

for example the primordial chemical fluctuation proposed should be hidden in the mean properties of the stellar populations of a galaxy (see Choi & Yi 2007).

7. New issue: UV-bright globular clusters in M87

The discovery of numerous UV-bright globular clusters in the giant elliptical galaxy M87 is also remarkable (Sohn et al. 2006). Using HST/STIS UV filters Sohn et al. found 66 globular clusters from small fields of view most of which are bluer and hotter than the Milky Way counterparts. Kaviraj et al. (2007) found that the canonical population synthesis models with normal values of helium cannot reproduce their UV properties at all, as shown in Figure 5. Kaviraj et al. found that their UV brightness can be reproduced if a similar amount of EHB stars found in the ω Cen study by Lee et al. (2005b) are artificially added to the canonical population models as well. This is very interesting. The more massive M87 is believed to contain 2 orders of magnitude more star clusters than the Milky Way does and thus it is very natural for us to find many more UV-bright globular clusters from M87 than from Milky Way. This can be compatible with the enhanced helium hypothesis. If the enhanced helium is present, say in 10% of the star clusters, roughly 10 clusters in the Milky Way and up to 1000

clusters in M87 might be helium-enhanced and thus UV-bright. A part of them may have been found by Sohn et al. (2006).

8. Conclusions

The UV satellite GALEX is obtaining a valuable UV spectral evolution data for numerous bright cluster galaxies. The apparent trend in redshift vs $FUV - V$ colour seems consistent with the prediction from the single stellar population models. This is comforting while observers feel obliged to build up their database much more substantially in order to make it statistically robust.

Two new issues are notable. Firstly, binary population synthesis community feels odd to find that the simplistic single-star population models are found to be good enough. The in-principle more advanced binary population models are obliged to reproduce the observed CMDs of simple populations (globular clusters) before attempting to model galaxies. For example, I am very eager to see their models reproduce the ordinary HB first, before explaining the EHB.

Secondly, the enhanced helium hypothesis based on the globular clusters in Milky Way and M87 is a very exciting possibility. The deduced value of the helium abundance seems unphysical to be a global property for the galaxy but may be possible for small systems that are vulnerable to a chemical fluctuation in the proto-galaxy cloud. While a more detailed investigation is called for it may be difficult to be influential to the entire stellar population of a galaxy. For instance, adding all spectral energy distributions of the Milky Way globular clusters would not yield anything close to the spectrum of a UV upturn galaxy. Of course, a metallicity difference may act as an added complication.

The secret will be revealed through time and hard work, perhaps very soon.

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